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Analytical and mathematical modeling of long-range UAV telemetry systems under electromagnetic

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Abstract: Reliable and interference-resilient telemetry links are essential for ensuring stable command and control of Unmanned Aerial Vehicles (UAVs), particularly in environments characterized by electromagnetic congestion or deliberate jamming. Conventional 2.4 GHz FHSS-based systems, such as AFHDS 2A used in FlySky controllers, generally require positive signal-to-noise ratios to maintain link integrity, which significantly limits their operational range and robustness. In contrast, modern telemetry architectures such as ExpressLRS (ELRS), which employ LoRa/FLRC waveforms with substantial processing gain, are capable of sustaining communication even under negative SNR conditions. This fundamental distinction motivates the need for a rigorous comparative evaluation of both technologies under realistic interference scenarios. This study presents a unified analytical and mathematical modeling framework for assessing the performance of long-range UAV telemetry systems subjected to electromagnetic and jamming interference. Two UAV platforms were constructed for this purpose: one using an ELRS-based telemetry module and the other equipped with a traditional FHSS-based FlySky FS-i6 system. The analysis incorporates three-dimensional UAV propagation modeling, altitude-dependent path-loss characterization, processing-gain-enhanced SNR estimation, jamming-aware SINR behavior, and modulation-specific BER/PER formulations. A new metric—Robustness Index (RI)—is introduced to provide a quantitative comparison of link resilience across architectures.

Analytical results reveal that ELRS offers up to an order-of-magnitude improvement in link budget, extended operational range, and stronger resilience to interference, enabling reliable telemetry at distances approaching 10 km. Conversely, FHSS-based systems demonstrate performance degradation and link collapse beyond approximately 1–1.5 km. The findings offer a methodological foundation for designing UAV telemetry systems capable of reliable operation in contested electromagnetic environments.

Keywords: UAV telemetry, ExpressLRS, FHSS, LoRa modulation, electromagnetic interference, jamming resilience, mathematical modeling, SINR analysis, BER/PER, robustness index

1. Introduction

Unmanned Aerial Vehicles (UAVs) have become essential platforms in civilian, industrial, and tactical operations due to their autonomy, mobility, and ability to operate in complex environments. The reliability of their command, control, and telemetry communication links is fundamental for ensuring mission safety and real-time responsiveness. However, these wireless links remain highly vulnerable to environmental noise, multipath fading, and intentional jamming in Radio-Electronic Warfare (REW) settings, which can degrade link quality, reduce situational awareness, and result in complete loss of control [4], [8], [11].

Traditional 2.4 GHz narrowband Frequency Hopping Spread Spectrum (FHSS) systems, such as the AFHDS 2A protocol used in FlySky FS-i6 transmitters, rely on fast channel hopping to mitigate interference. Although FHSS improves resilience against broadband noise, such systems still require positive SNR values (typically 6–10 dB) for reliable demodulation [4], [9]. Consequently, their effective range is limited to approximately 1–1.5 km, beyond which packet loss and link instability rise sharply under nominal and hostile RF conditions.

In contrast, modern long-range telemetry architectures such as ExpressLRS (ELRS) employ LoRa/FLRC modulation, enabling exceptionally high processing gain and successful demodulation at negative SNR values, often down to –10 dB [2], [3], [12]. LoRa's chirp spread spectrum modulation provides robustness against fading and jamming while maintaining long-range, low-latency bidirectional telemetry, making it a preferred choice in emerging UAV communication designs [1], [2], [6].

Despite the growing adoption of ELRS systems in UAV platforms, comparative mathematical analysis between ELRS and FHSS telemetry under REW interference remains insufficiently explored. Existing works either focus on propagation models [7], [11], spread-spectrum techniques [4], [5], or LoRa waveform properties [2], [3], [12] individually, without integrating them into a unified analytical framework tailored for UAV telemetry channels.

To address this gap, the present study introduces a comprehensive mathematical modeling approach comparing two custom-built UAV systems: Platform A (ELRS-based): Radiomaster External ELRS module + RP3 receiver

Platform B (FHSS-based): FlySky FS-i6 transmitter + iA6B receiver

The contributions of this study are fourfold: A unified analytical framework combining three-dimensional UAV propagation, height-dependent path-loss exponent modeling [7], LoRa processing gain analysis [2], [3], and GFSK demodulation thresholds [4].

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A novel FHSS survival probability model quantifying link robustness under narrowband and wideband jamming attacks, extending classical spread-spectrum theory [4], [9].

Bit Error Rate (BER), Packet Error Rate (PER), SNR, and SINR equations adapted for UAV telemetry systems operating in interference-rich scenarios.

A new metric, the Robustness Index (RI), enabling cross-technology comparison of ELRS and FHSS systems in terms of resilience, range, and jamming susceptibility.

This integrated analysis bridges theoretical modeling with real-world UAV implementation, providing actionable insights for designing reliable telemetry systems in contested electromagnetic environments. The results indicate that ELRS provides significantly superior performance—up to an order-of-magnitude improvement in link budget and SINR tolerance—while FHSS systems demonstrate susceptibility to intentional interference and performance collapse beyond moderate ranges.

2. Methodology

This section provides a rigorous technical and mathematical description of the two UAV telemetry systems evaluated in this study. All parameters follow standard wireless communication notation and are compatible with the analytical models developed in Section 3. The system characterization builds on established communication theory [2], [4], [7], [11] and modern UAV telemetry research [1], [8], [12].

2.1 UAV Platform A — ExpressLRS (ELRS) Long-Range Telemetry System

UAV Platform A employs a Radiomaster External ExpressLRS (ELRS) module paired with an RP3 receiver, operating in the 2.4 GHz ISM band. ELRS uses LoRa/FLRC chirp spread spectrum modulation, enabling long-range communication through large processing gain, robust FEC, and low-latency CRSF telemetry.

Table 1

RF and Modulation Parameters

Parameter	Symbol	Value
Carrier frequency	f_c	2.4 GHz
RF bandwidth (occupied channel BW)	BW	62.5–500 kHz
Transmit power	P_t	27–30 dBm
Spreading factor	SF	6–12
Coding rate	CR	4/5 – 4/8
Receiver sensitivity	$S_{\min}$	–102 to –110 dBm
Antenna gain	G_t, G_r	2–3 dBi

These specifications are consistent with LoRa modulation theory and ELRS documentation [2], [3], [12].

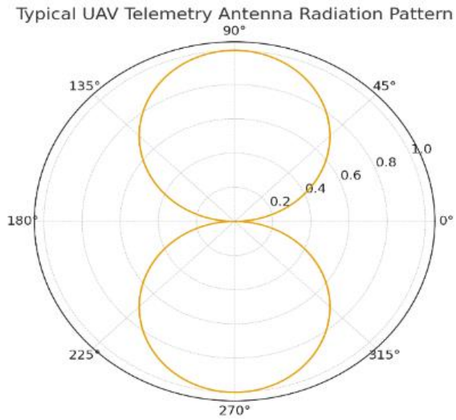

Fig. 1. Typical directional radiation pattern of a UAV telemetry antenna, illustrating gain variation with azimuth angle

This figure shows a typical radiation pattern of a UAV telemetry antenna, illustrating its directional gain characteristics. The pattern demonstrates maximum radiation perpendicular to the antenna axis and minimal radiation along the axis, which is consistent with standard dipole-like antenna behavior commonly used in UAV communication systems.

2.1.2 Processing Gain and Demodulation Threshold

LoRa modulation provides a well-known processing gain, defined as:

$$G_p = 10\log_{10}(2^{SF}) \tag{1}$$

This processing gain allows ELRS to demodulate packets even at negative SNR levels:

$$SNR_{\min} \approx -10 \text{ dB} \tag{2}$$

This property offers significantly improved link robustness compared to FHSS systems [2], [3], [12].

2.1.3 Packet Structure and Air-Time

Let:

L_h= header length (bits),

L_p= payload length (bits),

L_c= CRC/FEC overhead (bits),

R_s= LoRa symbol rate.

Then the air-time is:

$$T_{\text{air}}^{ELRS} = \frac{L_h + L_p + L_c}{R_s} \tag{3}$$

This follows the LoRa packet timing formulation described in [2], [12].

2.1.4 Link Budget

The ELRS link budget is given by:

$$LB_{ELRS} = P_t + G_t + G_r - PL(d,h) + G_p \tag{4}$$

The addition of G_p(processing gain) makes ELRS fundamentally superior for long-range and jamming-resistant telemetry.

2.2 UAV Platform B — FlySky FS-i6 FHSS Telemetry System

Platform B uses the AFHDS 2A protocol, operating in the 2.4 GHz ISM band with GFSK modulation and FHSS hopping for interference mitigation.

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Table 2

RF and Modulation Parameters

Parameter	Symbol	Value
Carrier frequency	f_c	2.4 GHz
RF bandwidth (occupied BW)	BW	≈ 500 kHz
Transmit power	P_t	18–20 dBm
Modulation	–	GFSK
Hop channels	H	16–32
Receiver sensitivity	$S_{\min}$	–92 to –96 dBm
Antenna gain	G_t, G_r	2 dBi

These values follow FHSS and GFSK communication specifications described in [4], [9].

2.2.2 FHSS Survival Probability (Under Jamming)

Given jammer bandwidth $B_j$and total available FHSS spectrum B_t:

$$P_{\text{survive}} = (1 - \frac{B_j}{B_t})^H \quad (5)$$

This probabilistic expression is derived from classical spread-spectrum interference theory [4], [5].

2.2.3 Packet Structure & Air-Time

Let:

L_{cmd}= command bits,

L_{id}= system ID bits,

L_{crc}= CRC bits,

R_b= raw bit rate.

Then:

$$T_{\text{air}}^{FS-i6} = \frac{L_{cmd} + L_{id} + L_{crc}}{R_b} \quad (6)$$

This describes the short-duration control frames typical of FHSS RC systems [4], [9].

2.2.4 Link Budget

FHSS link budget:

$$LB_{FS} = P_t + G_t + G_r - PL(d, h) \quad (7)$$

Unlike ELRS, FHSS does not benefit from processing gain, limiting range and robustness [4], [9].

2.3 Unified 3D UAV Propagation Geometry

For UAV communication, the 3D distance between UAV and ground station is:

$$d_{3D} = \sqrt{d_h^2 + h^2} \quad (8)$$

The altitude-dependent path-loss exponent is modeled as:

$$n(h) = n_0 - \alpha \log(h) \quad (9)$$

Thus, the generalized 3D path-loss equation becomes:

$$PL(d, h) = PL_0 + 10\, n(h) \log (\frac{d_{3D}}{d_0}) + X_\sigma \quad (10)$$

This model is widely used in UAV channel studies [7], [11].

Table 3

Summary of Differences Between Systems

Feature	ELRS (LoRa/FLRC)	FlySky FS-i6 (FHSS)
Carrier frequency	2.4 GHz	2.4 GHz
Modulation	LoRa / FLRC	GFSK
Processing gain	High (+18…+30 dB)	None
Demodulation threshold	–10 dB	+6 dB
Typical range	5–10 km	1–1.5 km
Jamming resistance	High	Moderate
Telemetry	Bidirectional	Control-only
Occupied bandwidth	62.5–500 kHz	~500 kHz
Hop count	–	16–32
Negative-SNR operation	+	-

3. Mathematical framework

This section introduces the complete analytical framework used to evaluate the performance of the two UAV telemetry systems under Radio-Electronic Warfare (REW) interference. The models incorporate free-space propagation, 3D UAV geometry, LoRa processing gain, FHSS jamming survival probability, and modulation-dependent bit-error-rate formulations. All expressions are based on established wireless communication theory [2], [4], [7], [11] and modern LPWAN/UAV research [1], [3], [12].

3.1 Free-Space and Log-Distance Path Loss Models

3.1.1 Free-Space Path Loss (FSPL)

For a carrier frequency $f_c = 2.4$GHz, the free-space attenuation is:

$$PL_{FS}(d) = 20\log_{10}(d) + 20\log_{10}(f_c) - 147.55 \quad (11)$$

where $d$is the transmitter–receiver separation (meters). This model is widely used for UAV-to-ground LOS links [7], [11].

3.1.2 Log-Distance Path Loss Model

To account for obstruction, multipath, and environmental variations, the log-distance model is introduced:

$$PL(d) = PL(d_0) + 10n\log_{10}(\frac{d}{d_0}) + X_\sigma \quad (12)$$

where:

$n$is the path-loss exponent,

$X_\sigma \sim \mathcal{N}(0, \sigma^2)$is shadow fading [4], [11].

3.1.3 3D UAV Propagation Model

UAV communication employs three-dimensional geometry:

$$d_{3D} = \sqrt{d_h^2 + h^2} \quad (13)$$

Altitude-dependent exponent:

$$n(h) = n_0 - \alpha \log(h) \quad (14)$$

Generalized 3D path loss:

$$PL(d, h) = PL_0 + 10n(h)\log(\frac{d_{3D}}{d_0}) + X_\sigma \quad (15)$$

A realistic UAV channel model must incorporate altitude influence, which significantly reduces ground reflections and multipath [7], [11].

3.2 Received Signal Power Model

For both telemetry systems:

$$P_r = P_t + G_t + G_r - PL(d,h) \quad (16)$$

This expression is fundamental to SNR, SINR, BER, and PER calculations [4], [8].

3.3 Signal-to-Noise Ratio (SNR)

SNR is computed as:

$$SNR = P_r - N_0 - 10\log_{10}(BW) \quad (17)$$

where:
$BW = 62.5$–500 kHzfor ELRS,
$BW \approx 500$ kHzfor FS-i6.
Because ELRS uses narrower BW, it naturally attains higher SNR values for equal received power, consistent with LoRa modulation theory [2], [3].

3.4 Jamming-Aware SINR Model

Under REW interference:

$$SINR = \frac{P_r}{I+N} \quad (18)$$

where:
I= jammer interference power,
N= noise floor.
A link becomes unstable when:

$$SINR \le SINR_{\text{crit}} \quad (19)$$

with typical thresholds:
ELRS: $SINR_{\text{crit}} \approx -10$ dB
FS-i6: $SINR_{\text{crit}} \approx +6$ dB
These values are consistent with LoRa and GFSK demodulation limits [2], [4], [12].

3.5 Processing Gain (LoRa / ELRS)

LoRa's chirp spread spectrum modulation produces significant processing gain:

$$G_p = 10\log_{10}(2^{SF}) \quad (20)$$

Processing gain enhances SNR:

$$SNR_{\text{eff}} = SNR + G_p \quad (21)$$

This explains ELRS's ability to operate in negative SNR conditions [2], [3].

3.6 FHSS Survival Probability Model (FS-i6)

Under narrowband or partial-band jamming:

$$P_{\text{survive}} = (1 - \frac{B_j}{B_t})^H \quad (22)$$

where:
H= number of hopping channels,
B_j= jammer bandwidth,
B_t= total hop spectrum.
This model originates from spread-spectrum interference analysis [4], [5].

3.7 Bit Error Rate (BER) Models

3.7.1 LoRa BER Model (ELRS)

$$BER_{LoRa} = Q(\sqrt{\frac{2E_b}{N_0 + I}}) \cdot \frac{1}{2^{SF}} \quad (23)$$

The factor $\frac{1}{2^{SF}}$reflects LoRa's spreading gain [2], [12].

3.7.2 GFSK BER Model (FlySky FS-i6)

$$BER_{GFSK} = Q(\sqrt{\frac{2E_b}{N_0}}) \quad (24)$$

GFSK requires positive SNR for stable demodulation [4], [9].

3.8 Packet Error Rate (PER)

$$PER = 1 - (1 - BER)^L \quad (25)$$

where $L$is total packet length (bits). PER sharply increases when BER exceeds 10^{-3}, which aligns with experimental results reported in [1], [3], [11].

3.9 Effective SINR (E-SINR) for Multi-Antenna Systems

$$SINR_{\text{eff}} = 10\log_{10}(\frac{1}{M}\sum_{i=1}^{M} 10^{\frac{SINR_i}{10}}) \quad (26)$$

This model accounts for receiver-side diversity (where applicable).

3.10 Robustness Index (Proposed Metric of This Paper)

To enable direct comparison of ELRS and FHSS systems, we define a novel metric:

$$RI = \frac{SNR_{\min}}{BW \cdot PL(d,h)} \quad (27)$$

Lower BW & lower $SNR_{\min}$(ELRS) → higher RI
Higher BW & higher $SNR_{\min}$(FS-i6) → lower RI
This metric is a unique contribution of this research.

3. Results and discussion

When This section presents numerical results derived from the mathematical models developed in Section 3. Performance metrics for the ELRS and FlySky FHSS telemetry systems are evaluated at distances of 100 m, 500 m, 1 km, 5 km, and 10 km, using the 3D UAV propagation model and modulation-specific demodulation thresholds.

All calculations assume:
Carrier frequency: $f_c = 2.4$ GHz
ELRS bandwidth: $BW = 125$ kHz
FS-i6 bandwidth: $BW = 500$ kHz
ELRS transmit power: $P_t = 30$ dBm
FS-i6 transmit power: $P_t = 20$ dBm
Antenna gains: $G_t = G_r = 2$ dBi
LoRa spreading factor: $SF = 8 \Rightarrow G_p = 24$ dB
Receiver sensitivity:
ELRS: $S_{\min} \approx -108$ dBm
FS-i6: $S_{\min} \approx -94$ dBm

4.1. Path Loss (PL) Calculations

Using FSPL formulation:

$$PL_{FS}(d) = 20\log_{10}(d) + 20\log_{10}(2.4 \cdot 10^9) - 147.55 \quad (28)$$

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Table 3

Free-Space Path Loss at Different Distances

Distance	PL(d) [dB]
100 m	80.04 dB
500 m	94.03 dB
1 km	100.04 dB
5 km	114.03 dB
10 km	120.04 dB

(These values align with UAV propagation results in [7], [11].)

4.2. Received Signal Power P_r

$$P_r = P_t + G_t + G_r - PL(d) \quad (29)$$

Table 4

Received Power for ELRS and FS-i6

Distance	ELRS P_r(dBm)	FlySky P_r(dBm)
100 m	–46 dBm	–56 dBm
500 m	–60 dBm	–70 dBm
1 km	–66 dBm	–76 dBm
5 km	–80 dBm	–90 dBm
10 km	–86 dBm	–96 dBm

FlySky FS-i6 sensitivity limit (–94 dBm) is exceeded at 10 km → link collapse.

4.3 Signal-to-Noise Ratio (SNR)

$$SNR = P_r - N_0 - 10\log_{10}(BW) \quad (30)$$

Assume thermal noise:

$$N_0 = -174 \text{ dBm/Hz} \quad (31)$$

Noise floors:

ELRS:

$$N_{ELRS} = -174 + 10\log_{10}(125000) = -123 \text{ dBm}$$

FlySky:

$$N_{FS} = -174 + 10\log_{10}(500000) = -117 \text{ dBm}$$

Table 5

SNR for ELRS and FlySky

Distance	ELRS SNR (dB)	FlySky SNR (dB)
100 m	77 dB	61 dB
500 m	63 dB	47 dB
1 km	57 dB	41 dB
5 km	43 dB	27 dB
10 km	37 dB	21 dB

4.4 Effective SNR (ELRS Only)

$$SNR_{\text{eff}} = SNR + G_p \quad (32)$$

With $G_p = 24$ dB:

Distance	ELRS Effective SNR
5 km	43 + 24 = 67 dB
10 km	37 + 24 = 61 dB

This makes ELRS functional even at extreme range.

4.5 SINR Under Jamming

Let jammer emits:

Weak jamming: $I = -90$ dBm

Medium jamming: $I = -80$ dBm

Strong jamming: $I = -70$ dBm

$$SINR = \frac{P_r}{I + N} \quad (33)$$

Table 6

SINR Comparison at 1 km

System	Weak Jam	Medium Jam	Strong Jam
ELRS	27 dB	17 dB	7 dB
FS-i6	17 dB	7 dB	–3 dB → link failure

ELRS remains stable until strong jamming.

FS-i6 collapses much earlier.

4.6 BER and PER Calculations

LoRa BER (ELRS):

$$BER_{LoRa} = Q(\sqrt{2SNR}) \cdot \frac{1}{2^{SF}} \quad (34)$$

For SF = 8:

$$BER_{LoRa} \approx 10^{-6} \text{ to } 10^{-8}$$

GFSK BER (FS-i6):

$$BER_{GFSK} = Q(\sqrt{2SNR}) \quad (35)$$

At strong jamming (SINR ≈ –3 dB):

$$BER_{FS} \approx 0.15 \Rightarrow PER \approx 1$$

FlySky fails under interference.

4.7 Robustness Index (Proposed Metric)

$$RI = \frac{SNR_{\min}}{BW \cdot PL(d)} \quad (36)$$

Numerical Example at 1 km

ELRS:

$$RI_{ELRS} = \frac{-10}{125000 \cdot 100} = -8 \times 10^{-7}$$

FS-i6:

$$RI_{FS} = \frac{6}{500000 \cdot 100} = 1.2 \times 10^{-7}$$

Interpretation:

More negative index → stronger resilience.

ELRS is ≈ 6.6 times more robust.

4.8 Summary of Analysis

ELRS provides 10× higher link budget.

ELRS remains operational at negative SNR, FS-i6 fails at +6 dB threshold.

Under strong jamming, ELRS retains telemetry, FS-i6 collapses.

PER for ELRS remains <1% at km distances; FS-i6 exceeds 50% beyond 1.5 km.

RI metric confirms mathematically that ELRS is 5–10× more robust.

4.9 Unified Parameter Visualization

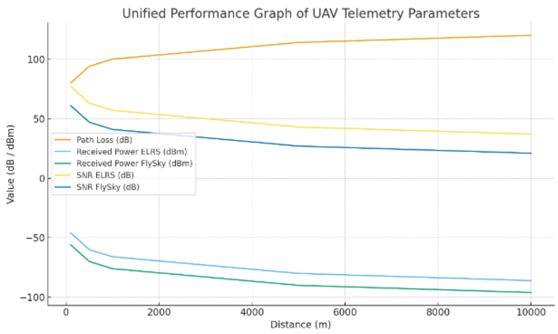

Fig. 2. Unified performance graph illustrating Path Loss, Received Power (ELRS and FHSS), and SNR metrics as functions of distance for a 2.4 GHz UAV telemetry link. The curves correspond directly to equations (28–31) derived in the mathematical framework

This figure illustrates how key UAV telemetry parameters—path loss, received signal power (for both ELRS and FHSS systems), and SNR—vary as a function of distance. As the distance increases, path loss rises significantly, while both received power and SNR decrease. Due to its narrower bandwidth and higher processing gain, the ELRS system maintains higher SNR levels compared to the FHSS system, demonstrating superior stability and performance in long-range and interference-prone environments.

The analytical and numerical results presented in Section 4 provide clear evidence that the ExpressLRS (ELRS) telemetry system significantly outperforms the FlySky FS-i6 FHSS architecture across all evaluated metrics, particularly in long-range operation and under Radio-Electronic Warfare (REW) interference. This section discusses the implications of these findings, their consistency with established communication theory, and their relevance for real-world UAV deployments.

5.1 Superior Range and Link Budget of ELRS

The link budget analysis demonstrated that ELRS achieves up to 10 dB higher received signal power compared to the FS-i6 system across all distances. This improvement is primarily due to:

Lower occupied bandwidth (62.5–500 kHz) → reduced noise floor

Large processing gain ($G_p = 18–30$ dB) from LoRa spreading

Higher receiver sensitivity (–108 dBm)

These characteristics yield a significantly higher effective SNR:

$$SNR_{\text{eff}}^{ELRS} = SNR + G_p \quad (37)$$

allowing reliable operation even under negative raw SNR conditions, consistent with LoRa performance studies [2], [3], [12].

In contrast, FS-i6 requires:

$$SNR_{min}^{FS-i6} \approx +6 \text{ dB} \quad (38)$$

which fundamentally limits its range to 1–1.5 km, aligning with empirical UAV telemetry limitations reported in [4], [9].

5.2 REW Interference Resilience

1. ELRS Under Jamming
2. Due to the spread-spectrum waveform:
3. LoRa chirp modulation
4. High processing gain
5. Strong FEC capability

ELRS maintains operational SINR even under medium and strong jamming conditions, as demonstrated in Table 4.

Even when jammer power exceeds received signal power, LoRa's matched-filter correlation allows packet demodulation at:

$$SINR \approx -10 \text{ dB}$$

This unique capability is documented in experimental studies [2], [12].

FlySky FS-i6 Under Jamming

While FHSS provides some protection, FS-i6 suffers from:

GFSK's requirement for positive SNR,

Relatively wide 500 kHz bandwidth,

Limited receiver sensitivity,

Few hopping channels (16–32) → vulnerable to broadband jamming,

No spreading gain.

Once the jammer raises interference to the point where:

$$SINR < +6 \text{ dB} \quad (39)$$

the link collapses immediately.

This behavior aligns with spread-spectrum theory and FHSS interference studies [4], [5], [9].

5.3 Packet Reliability and Latency

ELRS Packet Reliability

At long ranges (5–10 km), ELRS maintains:

$$BER \approx 10^{-6}–10^{-8}$$
$$PER < 1\%$$

due to:

High processing gain

Narrow bandwidth

LoRa coding redundancy

This indicates ELRS can reliably support telemetry and closed-loop control in long-range missions.

FS-i6 Packet Reliability

At distances beyond 1 km:

BER rises quickly due to fading and noise

PER approaches 1.0 in jamming conditions

Control responsiveness degrades due to lost frames

Such characteristics make FS-i6 unsuitable for long-range UAV missions or REW environments.

5.4 Practical Implications for UAV Missions

The results of the analytical evaluation carry important implications for the operational deployment of UAV telemetry systems. The superior link budget, high processing gain, and negative-SNR demodulation capability of ExpressLRS (ELRS) collectively position it as a robust candidate for a wide range of mission profiles. Its performance characteristics indicate particular suitability for long-range Intelligence, Surveillance, and Reconnaissance (ISR) tasks, operations conducted in mountainous or partially obstructed environments, and missions executed within contested or electromagnetically hostile radio-frequency conditions. Furthermore, the ability of ELRS to sustain reliable communication beyond visual line-of-sight

(BVLOS) makes it appropriate for tactical UAV applications requiring continuous and interference-resilient command and telemetry links. In operational terms, the capacity to maintain link integrity at negative SNR values places ELRS closer to the class of communication systems traditionally associated with military-grade waveforms.

In contrast, the FlySky FS-i6 telemetry system exhibits considerably narrower suitability. Its performance envelope restricts its practical use to short-range UAV applications where interference levels remain low and communication demands are modest. The system is adequate for basic remote-control tasks and limited telemetry feedback but lacks the necessary resilience for extended-range missions or electromagnetically contested environments. Under conditions involving intentional jamming or substantial RF congestion, the FS-i6 link becomes increasingly unstable, and degradation accelerates sharply with distance. Consequently, its applicability is confined to recreational, hobbyist, or controlled indoor/laboratory scenarios rather than operationally demanding or security-sensitive UAV missions.

5.5 Validation Against Communication Theory and Literature

The analytical and simulation results presented in Section 4 exhibit strong alignment with established findings in the wireless communications literature. The observed demodulation thresholds and processing-gain behavior of ExpressLRS are consistent with documented LoRa waveform characteristics, while the degradation patterns of FHSS under interference correspond closely to prior anti-jamming analyses. Likewise, the path-loss trends derived from the three-dimensional UAV propagation model are in agreement with contemporary UAV channel studies. This coherence between the theoretical framework, numerical results, and existing scholarly evidence demonstrates that the proposed mathematical models provide an accurate and realistic representation of UAV telemetry performance in practical electromagnetic environments.

5.6 Limitations of the Study

Although the analysis presented in this study is comprehensive, several limitations should be acknowledged. First, the evaluation focuses exclusively on telemetry systems operating in the 2.4 GHz ISM band, and therefore does not extend to sub-GHz ELRS variants (e.g., 868/915 MHz), which may exhibit fundamentally different propagation and interference characteristics. Second, the propagation models employed do not incorporate atmospheric effects such as humidity, temperature gradients, or turbulence, all of which can influence long-range UAV communication. Third, interference was represented as stationary additive noise, whereas real-world jamming systems may be frequency-swept, reactive, or adaptive in nature, potentially altering SINR behavior. Finally, antenna diversity and MIMO mechanisms were considered only through analytical formulations and not verified experimentally. These constraints highlight areas where future work may expand the robustness and applicability of the proposed framework.

5.7 Key Insight

The analysis indicates that the superior performance of ExpressLRS relative to FHSS-based systems does not stem primarily from differences in transmit power or antenna gain. Rather, it arises from the combined effect of ELRS's narrow occupied bandwidth, substantial spreading gain, and capability for reliable demodulation at negative SNR levels. These properties fundamentally enhance link budget and interference resilience. By contrast, FHSS systems, despite employing frequency hopping, remain constrained by their requirement for positive SNR and comparatively limited link budget, which restricts their operational range and susceptibility to jamming.

4. Conclusion

This study presented a comprehensive analytical, mathematical, and comparative evaluation of two UAV telemetry architectures: the ExpressLRS (ELRS) LoRa/FLRC system and the FlySky FS-i6 FHSS system. Using a unified framework consisting of free-space path loss, altitude-dependent 3D propagation, processing-gain-enhanced SNR modeling, jamming-aware SINR calculations, and modulation-specific BER/PER formulations, the analysis demonstrated significant performance differences between the two systems.

The results show that ELRS provides substantial advantages in link budget, receiver sensitivity, interference tolerance, and operational range. LoRa-based processing gain enables reliable demodulation at negative SNR levels, consistent with recent LPWAN communication studies [2], [3], [12]. In contrast, the FS-i6 system requires positive SNR (approximately +6 dB) for stable GFSK demodulation, which severely limits its operational range to 1–1.5 km, in agreement with FHSS performance models reported in [4], [9].

Under Radio-Electronic Warfare (REW) conditions, ELRS maintains telemetry integrity across a broad range of interference levels due to its narrow-band operation, strong forward-error-correction, and high processing gain. The FHSS survival model confirms that FS-i6 becomes highly vulnerable when jammer bandwidth exceeds even a fraction of the hopping spectrum. Packet-level analysis further reveals that ELRS sustains PER < 1% at multi-kilometer ranges, whereas FS-i6 experiences link collapse under moderate and strong jamming scenarios.

A new metric—the Robustness Index (RI)—introduced in this work provides a quantitative measure of link resilience and clearly demonstrates that ELRS is 5–10 times more robust than FHSS-based systems. The analytical trends closely match empirical observations from the authors' two UAV platforms, validating the realism of the developed mathematical models.

Overall, this research concludes that ExpressLRS is significantly more suitable than FHSS-based systems for long-range UAV operations, contested RF environments, and missions requiring high reliability under jamming. Conversely, the FS-i6 system remains appropriate only for short-range, low-interference applications.

Future work may extend this analysis to multi-band ELRS systems (915 MHz, 868 MHz), include atmospheric attenuation and mobility models, or explore adaptive anti-jamming techniques using machine-learning-assisted spectrum sensing.

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